Muon Acceleration with Non-Scaling FFAGs

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FFAG 2014
September 23, 2014

Accelerating Muons

- Muons decay rapidly
  - Acceleration must be rapid: collider targets average 3.5 MV/m
  - High frequency RF (325 MHz and higher)
- Large longitudinal emittances
  - Collider: 25 meV s RMS; large for desired frequencies
  - Need to limit longitudinal emittance growth
- Large bunch current
  - Beam loading may limit passes
- Control cost
  - RF efficiency: more passes through RF cavities
  - Magnet apertures

Machines for Muon Acceleration

- Recirculating lienar accelerators
  - High average accelerating gradient
  - Large longitudinal acceptance
  - Limited number of passes (switchyard)
- Pulsed (hybrid) synchrotrons
  - Many passes
  - Only work for high energies: magnet pulse time
- Non-scaling FFAGs
  - No switchyard to limit passes
  - Serpentine acceleration: nothing pulsed
  - Passes limited by decay, longitudinal emittance growth
  - More efficient at higher energies

Muon Colliders and Neutrino Factories

	Neutrino Factory	Muon Collider
Transverse emittance	large	modest
Longitudinal emittance	large	3× higher
Energy	5–10 GeV	high
Allowed loss	some	low
Allowed emittance growth	some	low
Beam current	modest	high

Neutrino Factory FFAGs

- Accelerating to 25 GeV, FFAGs looked attractive
  - About 11.5 passes, more than possible with RLA
- Nonlinear transverse to longitudinal coupling increases effective longitudinal emittance
- Preferred energy changed to 10 GeV
  - Cost comparable to RLA
  - Fewer passes at optimum cost
    - Longitudinal emittance relatively larger fraction of phase space
    - Transverse beam size makes a larger relative contribution to aperture

Muon Collider FFAGs

- Hope for better applicability
  - Small transverse emittance
    - Negligible transverse to longitudinal coupling
    - Small contribution of beam size to aperture
  - High energies, so better efficiency
- Challenges beyond neutrino factories
  - Even larger longitudinal emittance, and strong need to control its growth
  - Importance of high accelerating gradient
- Two cases considered
  - Replace 63–375 GeV, 10 turn non-hybrid pulsed synchrotron with two FFAGs
  - Replace RLA up to 63 GeV with FFAG(s)

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Muon Collider FFAGs

- FFAGs from 63 to 173 GeV and 173 to 375 GeV
  - Could win: non-hybrid synchrotron less efficient than hybrid
  - FFAG solution is over twice the cost
  - Cannot get up to 10 turns
  - Long circumferences to control longitudinal emittance growth
- FFAG from 25 to 63 GeV
  - Only 4 turns, even at 325 MHz
    - Longitudinal emittance growth
    - Decay requirements
  - Long circumference to control longitudinal emittance growth

Muon Collider FFAGs

Min. Energy (GeV)	25	63	173
Max. Energy (GeV)	63	173	375
Turns	4.0	5.3	8.5
RF Frequency (MHz)	325	650	975
Circumference (km)	5.1	4.8	5.7

Details: doi:10.2172/1119569

Better FFAGs for Muon Colliders

- Less longitudinal emittance growth for a given circumference
- Use sextupoles to reduce time of flight range
- Impact on dynamic aperture
  - Modest transverse emittances in colliders
  - Small number of turns
- Remaining sextupole knob: aperture?
- Add higher harmonic RF
  - But watch out for beam loading

Conclusions

- FFAGs looking unattractive for muon acceleration
  - Low neutrino factory energies
  - Controlling longitudinal emittance growth and decay for colliders
    - Made difficult by large longitudinal emittance
- Best avenue for improvement is reduction of longitudinal emittance growth
  - Adding sextupoles to reduce time of flight range
    - Easier for colliders than neutrino factories
- May revisit as longitudinal emittance control is making RLAs look more expensive as well